

3rd International Meeting of the Union for Compact Accelerator-driven Neutron Sources,
UCANS III, 31 July–3 August 2012, Bilbao, Spain & the 4th International Meeting of
the Union for Compact Accelerator-driven Neutron Sources, UCANS IV,
23–27 September 2013, Sapporo, Hokkaido, Japan

A conceptual description of the ESS-Bilbao accelerator

I. Bustinduy^{*a}, F.J. Bermejo^b

^aESS-Bilbao Consortium, Bizkaia Technology Park, Laida Bidea, Building 207 B Ground Floor, 48160 Derio (Spain)

^bConsejo Superior de Investigaciones Científicas, C.S.I.C., Instituto de Estructura de la Materia, Serrano 123, Madrid 28006, Spain

Abstract

The ESS-Bilbao (ESSB) light ion linear accelerator is conceived as a multi-purpose machine that will serve as a driving force for the construction of the European Spallation Source (ESS). The first part of the ESSB injector comprises a proton source of the Electron Cyclotron Resonance (ECR) kind. The low energy beam is transported along a two solenoid Low Energy Transport System (LEBT) that will couple the ion source to the 352.2 MHz Radio Frequency Quadrupole (RFQ). This RFQ –based on a modular design where the vane sections are held in place by bolts, and the welds only serve to make the structure vacuum tight, aims to accelerate a 75 mA beam from 45 keV up to 3 MeV, while keeping the beam both transversely and longitudinally focused together with minimum emittance growth. Once the RF timing structure is set to the beam, it is conveniently matched through the Medium Energy Beam Transport (MEBT) to the Drift Tube Linac (DTL), which will take this 3 MeV beam up to the required energy by the designed Be rotating target (50 MeV).

© 2014 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license

(<http://creativecommons.org/licenses/by-nc-nd/3.0/>).

Peer-review under responsibility of the Organizing Committee of UCANS III and UCANS IV

Keywords: Ion Source; LEBT; RFQ; MEBT; DTL; ESS-BILBAO;

1. Introduction

At the time of writing the facility so designed comprises a 50 MeV linac composed by two room-temperature accelerator structures, namely a Radio-Frequency-Quadrupole and a Drift-Tube-Linac together with matching sections such as the Low Energy Beam Transport and Medium Energy Beam Transport. The 50 MeV proton beams from the linac, having parameters listed in Table 1, are then transported to applications laboratories devoted to the studies of proton radiation effects on a variety of systems and devices as well as a neutron production target based upon direct

^{*} Corresponding author.

E-mail address: ibon.bustinduy@essbilbao.org

(p, n) reactions on Be targets.

Table 1. An example of a table.

Element	Length (m)	Energy (MeV)	No. cavs.	No. gaps	FR pow. (MW)	No. klystrons
Ion Source	1.5	0.045				
LEBT	3					
RFQ	3.2	0.045-3	1	306 cells	1.2	1
MEBT	1.3	3	2	2 buncher	0.15	
DTL	14.6	3-50	3	108 DTs	3.8	3

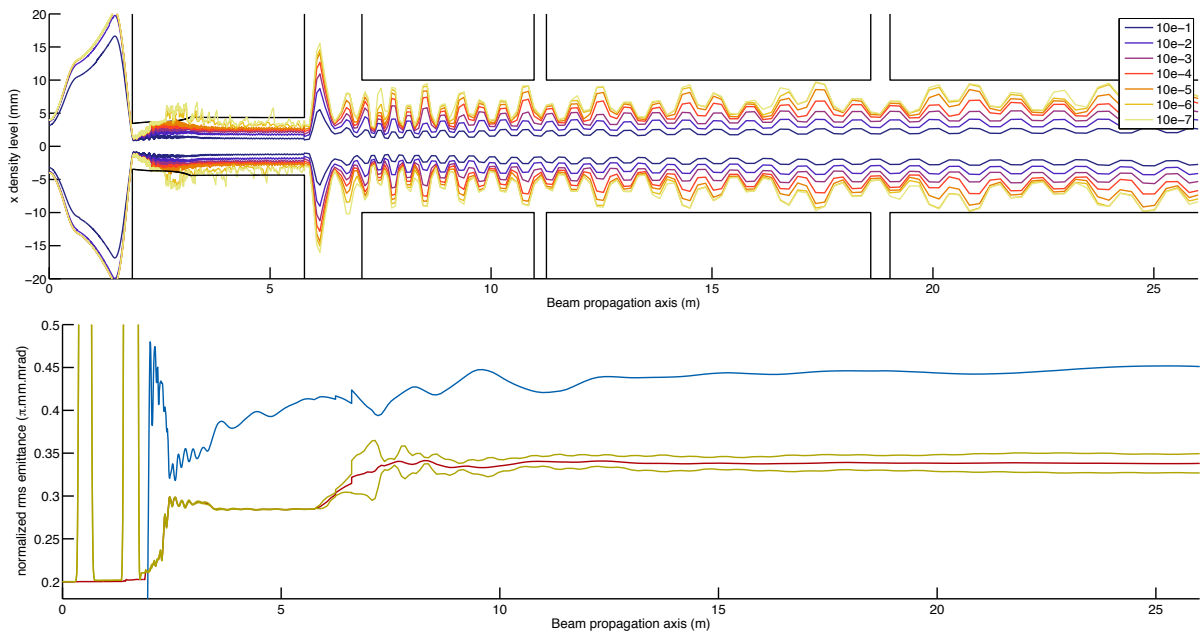


Fig. 1. *Top*: x density levels projections along the entire linac: LEBT, RFQ, MEBT and DTL. *Bottom*: Normalized rms emittance values longitudinal (blue) and transverse (red)

The Fig. 1 displays power density levels of the beam along the entire linac. In the bottom frame the normalised emittance values are represented. Those *end-to-end* simulations are essential to define and constrain the layout, evaluate the robustness of the linac against both time-dependent (fast) errors due to mechanical vibrations, power supplies jitters, etc. And, static errors, produced by possible misalignments, or off-sets in the RF and magnetic elements.

Fig. 4, and Fig. 9 represent power density along the accelerator, please note that each part of the accelerator has a different colour scale. In the first case, range goes from 10^{-4} to 10^3 W. Aperture of the Solenoids aperture ($\varnothing 100$ mm) is ~ 2.5 times bigger than the filled area by the beam. 10^3 W values are reached at the last part of the RFQ –confined in $\varnothing 2.6$ mm; RFQ vane tips closer distance is ~ 5.1 mm. In Fig. 9, range goes from 10^{-2} to 10^5 W. 10^5 W power is only reached at the last tank of the DTL, and is enclosed in $\varnothing 2$ mm. In this last section, beam pipe is ~ 10 times larger. A dipole to avoid neutron back streaming and set of 3 quadrupoles to defocus beam on Be target is foreseen. Each of the sections that conform the linear accelerator will be explained in the following sections:



Fig. 2. Image of the Ion source. RF power is transmitted from left to right. The plasma chamber and the magnet coils are water cooled. The outer part of the extraction column made from alumina is depicted in its characteristic white colour.

2. Ion Source

The accelerator at ESS-Bilbao is intended to use an Electron Cyclotron Resonance (ECR) H^+ source. The production of positively charged hydrogen ions is far simpler than that of negatively charged ones, since there is no need to add electron donors [Moehs et al. (2005)]. ECR sources are relatively simple, especially when compared to Penning sources, they can be turned on almost instantaneously and have shown a long lifetime.

The ion source is composed of a CPI S-Band 2.7 GHz Klystron amplifier that provides the RF power. The ECR field is generated by a set of two coil pair that can be moved to change the shape of the magnetic field profile. This field profile is also controlled by the current supplied to each coil. The Hydrogen flow into the chamber is controlled by a mass-flow controller from Omega Engineering. The entire microwave system has been tested in continuous wave and pulsed modes, and plasma ignition repetitiveness is assured. The high voltage platform for the source has been successfully tested up to 70 kV, with the power from the isolation transformer.

The extraction column was designed so that the distance between the plasma electrode and the extraction triode system could be displaced while in vacuum. This tetrode system is composed of a 45–75 kV plasma electrode¹ and an puller electrode (ground) placed at the so called *accelerating gap* distance, so that the electric field strength E is given by the voltage applied to the plasma electrode and this distance. This puller electrode is followed by a suppressor electrode fed at -3 kV (max). The tetrode system is completed with a ground electrode placed after the suppressor electrode.

¹ Platform voltage range goes from 45 keV up-to 75 keV

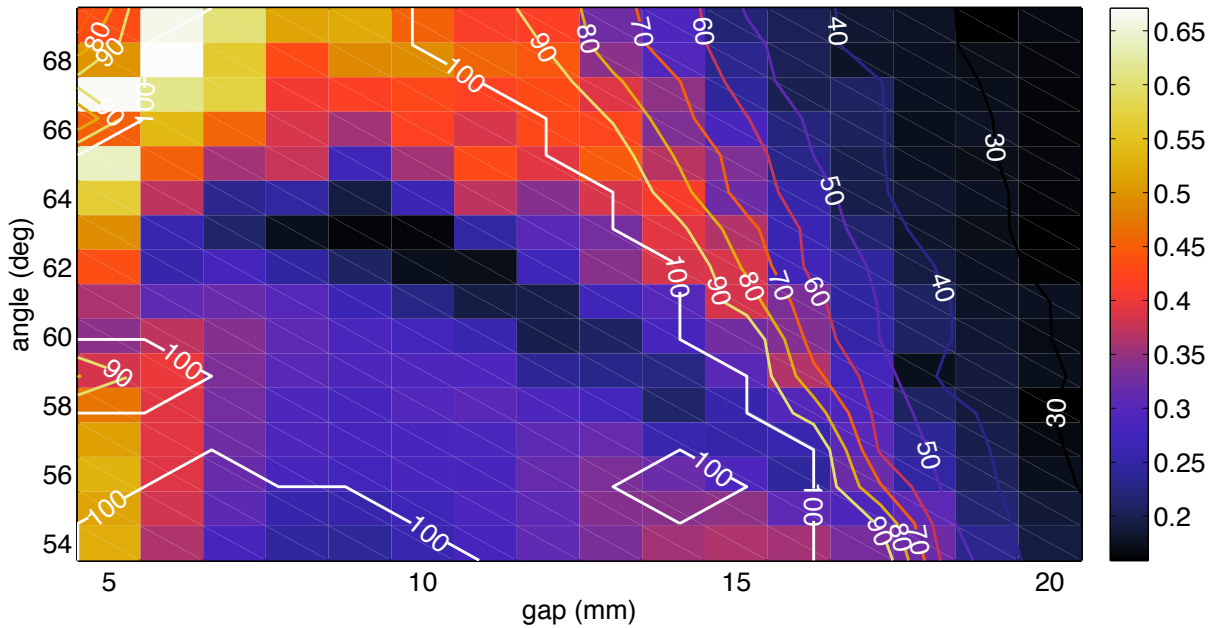


Fig. 3. Parametric study when platform voltage is set to 75 kV for different combinations of: accelerating gap and plasma electrode angles. Colormap represents normalised transverse emittance values at 500 mm. Contour lines represent beam transmission (in percentage units).

The extraction system intrinsically determines the current of the beam and its quality, it is therefore a critical part of the ECR source where a strong magnetic field traps the plasma. An optimal electrode shaping is fundamental to extract a well focused beam with high current and low emittance. The performance of this kind of extractors in similar ECR sources was already demonstrated numerically and experimentally [Sherman et al.].

Although the spherical shape extraction system have been shown to lead to higher currents, a parametric solution study based upon the Pierce [Pierce (1949)] shape presented a more stable solution [Fernandez et al. (2010)]. This particular shape of accelerating electrodes is often used by space charge dominated extraction systems where undesired forces ² can be more easily minimised.

The Fig. 3 represents part of the set of simulations (extraction gap, plasma electrode and puller electrode geometry, etc.) that were required to cover the full spectrum of geometric solutions for the ECR source. In such figure we can see that, apart from the solution found for gap= 14 mm and $\theta = 31^\circ$ the emittance comparison across different geometries can only be done when the beam is fully transmitted. Therefore, the low emittance area found for high values of the gap is discarded. Those simulations were performed to obtain an electrode system capable of extracting, accelerating, and delivering a high quality proton beam from the plasma chamber to the LEBT system. Moreover, the normalised RMS emittance at the LEBT position must be kept below 0.2π -mm-mrad in order to get an acceptable matching to the elements downstream the accelerator.

3. LEBT

The role of the LEBT, placed between the ion source and the RFQ, is to match the beam characteristics to the RFQ input specification. The proposed magnetic Low Energy Transport System (LEBT) consists of two solenoids placed

² Radial electrostatic fields confined with longitudinal component of the magnetic field produced on the ECR solenoids

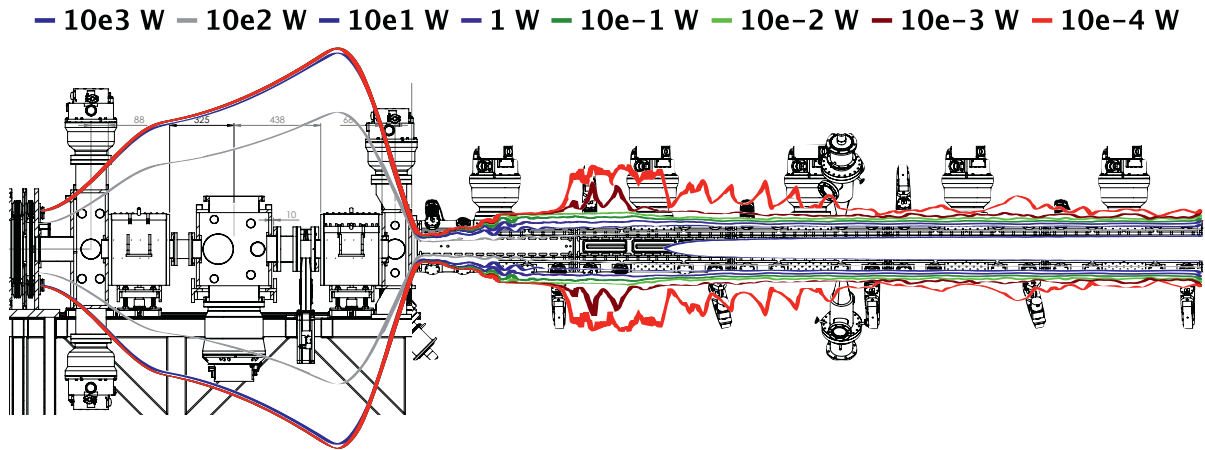


Fig. 4. Two solenoid layout proposed for the LEBT and 5 segment RFQ, accompanied by the expected five ion pumps, ten slug tuners and two couplers. On top of it, projections of power density probability in the r plane is represented. Beam zenith occurs at the entrance of the second solenoid where it takes $\varnothing 40$ mm.

at fixed positions, producing tuneable magnetic fields which are used to match the characteristics of the beam to those imposed by the RFQ input specification.

Although an electrostatic LEBT was also studied [Becker and Bustinduy (2009)] for the H^- source, the first layout [Bustinduy, et al. (2010)] was based on a revolver-type mechanism made by four solenoids, designed to transport both H^+ and H^- beams (see Fig. 5). The main drawback of this layout was that ion sources may not be plugged-in simultaneously and thus a considerable amount of time is wasted each time the ion sources are switched and the accelerator has to be put back to operation. In order to reduce this time a new layout was presented [Bustinduy, et al. (2011)]. This Y-shaped LEBT design—similar to the one proposed in the SNS upgrade plans [Han, et al. (2007)], which would allow for a rapid switching between the two ion sources. In this layout two ion sources were connected by means of a sector magnet, where the rest of the components were planned to be reused from the previous design. Once all resources were focused primarily on H^+ source the LEBT layout got simplified to only two solenoids.

The ECR H^+ source outcome is an axysimetric beam that can be matched to the RFQ input requirements with only two solenoids. The use of redundant solenoids would imply an increase in the emittance, affecting thus the effective transmission of the linac. Two different studies were performed:

Error studies: To evaluate robustness the design of the LEBT against static errors, produced by possible misalignments, or off-sets in the magnetic field provided by the solenoid and power supplies.

Layout studies: To evaluate the maximum length of the drift spaces that define the LEBT, we can tolerate without affecting beam quality.

Input Condition studies: To evaluate the effect of the input conditions variation: energy, emittance, beam current, etc.

The solenoids use a smaller internal radius (involving more turns) at the ends than in the centre. In such a way, the magnetic field profile along the axis is flatter than the one achieved with a uniformly shaped solenoid. Besides, the variable radius approach creates a magnetic field that remains confined within the solenoid limits, avoiding perturbations on any nearby elements. In order to save beam-line space, the proposed design includes the ability to nest dipoles and solenoids together. This dipole-solenoid assembly is composed by a solenoid integrated together with a set of two crossed ($x-y$) dipoles of the $\cos \theta$ type. The dipoles are capable of steering the beam to correct for misalignment of the beam line components, reaching a deflection of up to $\pm 4^\circ$ for protons. The presence of the dipoles limits the



Fig. 5. Testing auxiliary systems: cooling, electrical systems, control and power supplies with 4 solenoid layout initially proposed for the LEBT.

aperture to 100 mm.

Self space charge neutralisation plays an important role in this part of the accelerator. The system has to be able to achieve a value of 10^{-5} mbar at its inlet, which is the pressure required for the ion source to operate. At the same time, it has to be able to maintain a value of 10^{-7} mbar, the maximum pressure acceptable for the RFQ to operate without arcing.

4. RFQ

The Radio Frequency Quadrupole (RFQ) is a device used in the low energy section of most of the modern RF linear accelerators (linacs) thus substituting the often used Cockcroft-Walton voltage multipliers as first injection steps. This structure thus has as its tasks bunching the initially DC beam, provide initial acceleration to such a beam and also to keep it focused within both transverse and longitudinal directions. The aim is to do that efficiently, thus minimising the number of particles which are lost by striking the accelerator structure during this process, since they will cause a radioactivity buildup over time.

The main processes which take place inside a RFQ as employed in applications where its main task is to increase the energy of an input beam are first, to form bunches from an initial *macro-pulse* typically a few \sim ms of duration into a train of \sim ns *micro-pulses* or bunches which thus form the temporal structure of the beam pulse to be accelerated.³ The structure then focuses and accelerates such bunches up to $\beta \approx 0.08$ times the speed of light. Both acceleration and focusing within this structure are thus provided by the field components of the injected Radio Frequency power.

The RFQ Design process [Bermejo et al. (2013)] constitutes a entangled problem on its own nature, the cavity has to fulfil some specific requirements from the electromagnetic point of view. The cavity has to be excited in an quasi- TE_{210} electric quadrupole mode, in order to provide a time varying quadrupole focusing field on axis. The goal

³ It goes without saying that several other types of acceleration devices based on pure electrostatics, induction machines etc. do not require the input beam to be decomposed into ns bunches.

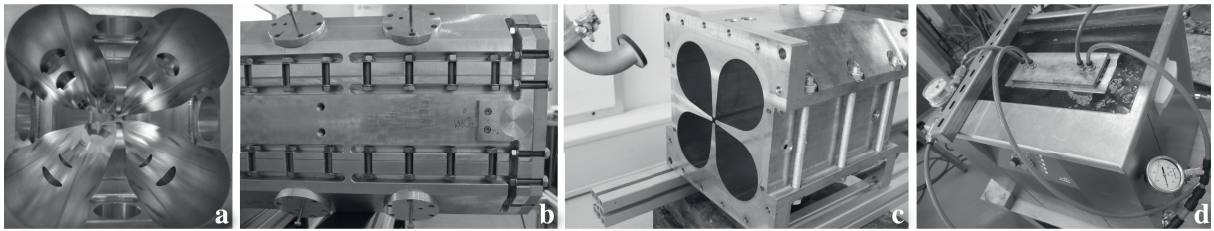


Fig. 6. RFQ prototypes. (a) inner view of the 1m long Al cold model. (b) detailed view of the bolted Al cold model. (c) Cu model to test different welding techniques at Imperial College London. (d) Cu model to test two different cooling schemes.

is to produce a flat field profile keeping the TE_{110} dipole modes away in frequency, while maximising the *effective shunt impedance* of the whole structure. Moreover, the desired fundamental mode (quadrupole) is required to be close to the final operating frequency of 352.2 MHz to match with the klystron and RF system.

End cells are carefully designed [de Cos et al. (2011)] in order to obtain an optimum shape that guarantees the field flatness along the structure and ensures that power deposition can be removed with the chosen cooling system. This power deposition in OHFC will derive in expansion of the material leading to variation in the conditions of the resonator and also possible variations in the shape of the vane profile, affecting thus the quality of the accelerated beam. As a consequence, slug tuning rods must be added in order to adjust the RFQ resonant modes, and possibly correct some imperfections in the machining process. Along with the tuners, the electromagnetic optimisation process has to fulfil several other constraints imposed by the inherent manufacturing procedures, cooling, etc.

In Fig. 6, a set of Cu prototypes and Al cold model is presented. In particular, the OHFC⁴ prototypes were designed and manufactured in order to test different welding methods as well as other mechanical aspects (vacuum leaks, cooling, etc.) involved in the manufacture of the RFQ. The 1m long cold model includes 16 slug tuners and 8 coupler/pick-up ports, which allow the use of the bead-pull perturbation method to measure the electric field profile, Q-value and resonant modes. In order to test fabrication tolerances, the cold model also included a longitudinal test modulation in the vanes. These models served as a good test bench to investigate the validity of different finite element analysis (FEA) software packages [I. Bustinduy et al. (2012)].

By its own nature within the RF resonant cavity a minimum pressure 10^{-7} mbar has to be achieved to avoid spark phenomena due to the generated electromagnetic fields, as well as to avoid scattering particles out of the beam, which increases two phenomena, namely emittance and radiation hazard.

5. MEBT

The major challenge of this part of the accelerator is to keep a high quality beam, with a pulse well defined in time, a low emittance and a minimised halo, so that the beam losses downstream the linac be limited and the overall reliability be maximised. In order to minimise beam loss at the higher energy linac, a compact layout is foreseen for the medium energy beam transport section (MEBT). The considered versatile MEBT is being designed to achieve three main goals namely, to serve as a halo scraping section by means of various adjustable blades. Second, to measure the beam phase and profile between the RFQ and the DTL, along with other beam monitors. And finally, to match the RFQ output beam characteristics to the DTL input both transversally and longitudinally. For this purpose a set of five quadrupoles is used to match the beam characteristics transversally, combined with two 352.2 MHz buncher cavities (see Fig. 7), which are used to adjust the beam in order to fulfil the required longitudinal parameters. The implementation of the long chopper MEBT layouts has also been studied [I. Bustinduy, et al. (2012)], but for the

⁴ Oxygen free high conductivity copper

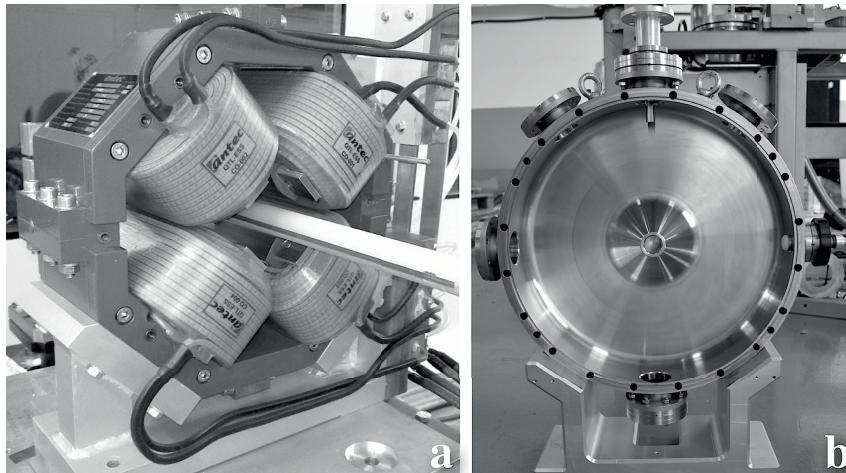


Fig. 7. Manufactured parts of the MEBT. (a) Quadrupole prototype being tested at ALBA Synchrotron. (b) ESS Buncher cavity prototype.

required long pulse (~ 1.5 ms) small angle neutron scattering (SANS) experiments, such *chopper lines* were finally discarded. In contrast, some other instruments such is the case for some spectrometers, efficient neutron chopping schemes might be implemented.

The magnet translation, rotation and quadrupole gradient errors were also studied, in order to narrow the requirements for the dipolar components needed for the quadrupoles. These steerers (embedded in the Quads) are demanded to correct the beam trajectories from misalignments produced due to manufacture imperfections or alignment errors during the installation phase of the different elements.

The use of scrapers before entering DTL tanks is strongly recommended to avoid emittance growth and halo development in high-intensity linacs [Gerigk, et al. (2002)]. In our current design, collimators should be able to scrap the beam in the both transverse plane at each locations. For this, a set of four step motors are needed per location. The scrapper will be used during nominal operation, the collimator system has to be integrated in the interlock system in order to avoid interaction with the beam core, the position of the beam will be provided by a beam position monitor positioned as close as possible to the collimator and the movement has to be limited. In addition, the temperature and charge deposition is measured in each scrapper.

6. DTL

The structure known as Drift Tube Linac or DTL is the most commonly used structure to accelerate H^+/H^- beams in the $0.03 < \beta < 0.4$ range of speeds (~ 0.5 MeV up to ~ 100 MeV), and thus it is included in most light ion linear accelerators. Generally the DTL structure operates in the ~ 200 -400 MHz frequency range. The complete system comprises various pillbox-type cylinder-shaped resonant cavities, each excited in a TM_{010} mode. Drift tubes are located to a nominal distance $\beta\lambda$, meaning a field-free distance during the period of time in which RF fields induced in the cavity are decelerating. Permanent magnets (PMQ) will be accommodated into the drift tubes in order to supply an alternating cross focalisation gradient. The accelerating RF field within each gap oscillates to the same phase and frequency, with the length of a cell given by: $l_i = \left(\frac{\varphi_{s,i+1} - \varphi_{s,i}}{2\pi} + 1 \right)$, where $\varphi_{s,i}$ is the synchronous phase for cell i , and β_i is the speed out of the cell. Accelerating gradients are usually constant from cell to cell, though in some cases, variations in the field are induced with the purpose of maintaining a smooth longitudinal focalizing structure. The adoption of a synchronous phase in each cell is selected in order to supply a longitudinal focalization (typically between -35° and -20°) and can be conveniently varied in order either to adjust phase acceptance or improve longitudinal adjustment or matching. At higher energies, the effective shunt impedance decreases until the DTL becomes a less efficient

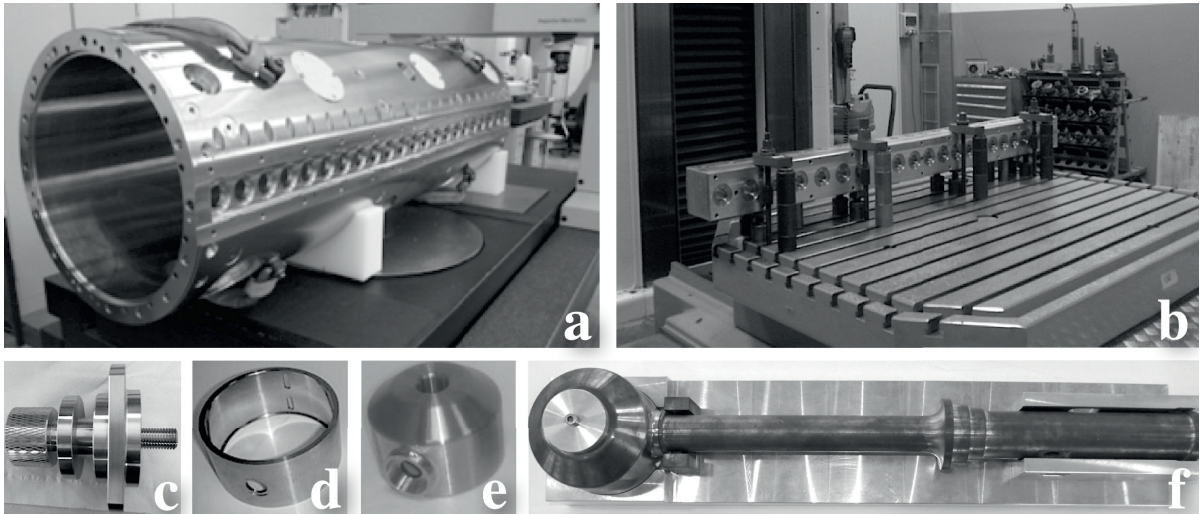


Fig. 8. Manufactured parts of the DTL. (a) First segment of tank 1. (b) Girder. (c) Traction screw, guide washer and socket assembled. (d) Separation ring. (e) Drift tube body. (f) Drift tube assembled.

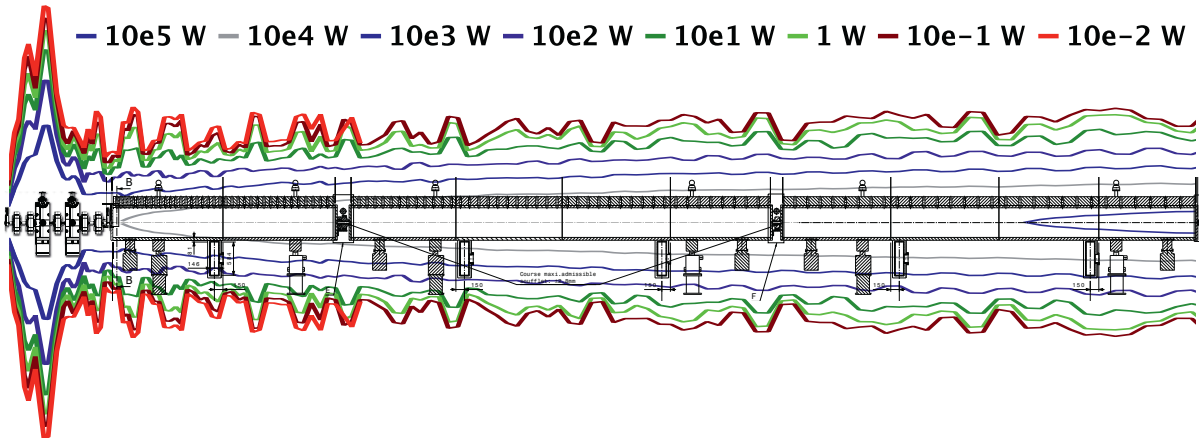


Fig. 9. Proposed short MEBT and 3 tank DTL. On top of it, power density probability of the particles onto the r plane are represented. Beam zenith occurs at the entrance of the second solenoid where it takes $\varnothing 36$ mm.

structure over ~ 100 MeV.

The current mechanical design of the ESS-Bilbao DTL is based upon results from a collaboration with the LINAC4 group from the CERN. The key features that describe the DTL at ESS-Bilbao are thus given, and this implies that the election of the quadrupole gradients along the DTL is totally constrained. This DTL is composed of 3 tanks with FFDD lattice, containing 113 permanent quadrupoles, 1 electromagnet quadrupole, and 2 steerers between tanks. This 352.2 MHz resonating structure accelerates the beam from 3 MeV up-to 50 MeV.

The key magnetic design aspect is to keep the ratio between the transverse and longitudinal phase advance constant at a value of around $k_t/k_l \sim 1.4$. This is done to avoid resonances, and the precise number comes from the ratio between the longitudinal and transverse emittances according to Hofmann's diagrams. If one plans to keep the mentioned ratio constant, and considering that as the particle gains energy the longitudinal RF defocusing force decreases (and hence also the longitudinal phase advance), it will be necessary to lower σ_{0r} by reducing the permanent magnet quadrupole (PMQ) gradients along the tanks. Acceleration fields up-to 3.3 MV/m for tank 1 and 3.5 MV/m for tanks

2 and 3 will be supplied by a power klystron coupled to each tank.

The local industry has already manufactured and delivered a first tank, girder, drift tube parts (see Fig. 8), and a set of permanent magnets intended for Linac4, fulfilling required specifications by CERN public tenders, as well as drift tubes and their support elements under contract from ESS-Bilbao.

Acknowledgments

Since its very inception, the project has largely benefited from the ongoing collaboration with some of our international partners involved in similar developments such as CIEMAT, INFN, CEA-Saclay, the new ISIS front-end test stand, the SNS facility at Oak Ridge Nat. Lab. as well as the Linac4 project at CERN. As a result, we received significant inputs originated in these facilities which are gratefully acknowledged. Finally, to all ESS-Bilbao co-workers who dedicated a substantial amount of their spare time to make things possible.

Codes: IBSIMU, GPT, NIGUN, MAD, TRACEWIN, TOUTATIS and RFQSIM.

References

References

- D. P. Moehs, J. Peters, and J. Sherman “Negative Hydrogen Ion Sources for Accelerators”, IEEE TRANSACTIONS ON PLASMA SCIENCE, VOL. 33, NO. 6, DECEMBER 2005.
- J. Sherman et al, Development of a 130-mA, 75kV High Voltage Column for High Intensity dc Proton Injectors. LANL Internal Report LA-UR-97-3282.
- J.R. Pierce, Theory and Design of Electron Beams, Van Nostrand, Princeton, NJ, 1949.
- D. Fernandez, I. Bustinduy, et al., Electrode Design of The ESS-Bilbao Accelerator Proton Extraction System, MOPD37. Proceedings of HB 2010, Morschach, Switzerland.
- R. Becker, I. Bustinduy. “H⁻ Ion source and LEBT design with nIGUN” ESS-Bilbao Initiative Workshop (Multi MW Spallation Neutron Sources: Current Challenges and Future Prospects), March 2009, Bilbao.
- I. Bustinduy, et al. “first LEBT Simulations For The Bilbao Accelerator Ion Source Test Stand”, Proceedings of HB2010, Morschach, Switzerland, THO1B05, (2010).
- I. Bustinduy, et al. “Low Energy Beam Transport Development for the Bilbao Accelerator”, Proceedings of 2011 Particle Accelerator Conference, New York, NY, USA, WEP011, (2011).
- B.X. Han, et al. “The New LEBT For The Spallation Neutron Source Power Upgrade Project” Proceedings of PAC07, Albuquerque, New Mexico, USA, TUPAS075 (2007).
- F.J. Bermejo, I. Bustinduy, et al. “Technical Design Report: ESS-BILBAO RFQ”, <http://essbilbao.org:8080/ESSBilbao/en/RFQTDR08.pdf> (2013)
- D. de Cos, I. Bustinduy, et al. “Beam Dynamics Simulations on the ESS Bilbao RFQ Proceedings of 2011 Particle Accelerator Conference”, New York, NY, USA MOODS6, (2011)
- I. Bustinduy et al., “Design and Fabrication of the ESS-Bilbao RFQ Prototype Models” Proceedings of IPAC2012, New Orleans, Louisiana, USA, THEPPB001 (2012)
- I. Bustinduy, et al. “Medium Energy Beam Transport Design Update for ESS” HB2012: Proceedings of the 52nd ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams, Beijing, MOP235 (2012)
- F. Gerigk, et al., “High Current Linac Design with Examples of Resonances and Halo”, Proc. XXI International Linear Accelerator Conference (LINAC 2002), Gyeongju, Korea, 19-23 Aug 2002
- J. Stovall and K. Crandall. “Quadrupole law and steering options in the linac4 DTL”. CERN publication, sLHC Project Note 0006, 11 2009.